SITE EVALUATION OF THE ASH WATER DENSE SUSPENSION PROCESS

FINAL REPORT

by

Elzbieta M. BULEWICZ*
Ewa ZOLDANI**
Krystyna DUDEK*

* Cracow University of Technology, Krakow, Poland
** Academy of Mining and Metallurgy, Krakow, Poland

Work on this project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources Canada. This work was supported, in part, by the Federal Panel on Energy R&D (PERD).

Acknowledgement: This work was also supported by Environment Canada via the Federal Interdepartmental Panel on Energy, Research and Development (PERD) and by Nova Scotia Power Corporation.

DSS FILE NO.: 039QS.23440-1-9061
DSS CONTRACT SERIAL NO.: 23440-1-9061/01-SQ
CANMET PROJECT NO.:
CANMET SCIENTIFIC AUTHORITY: Dr. E.J. Anthony
Energy, Mines and Resources
CANMET, ERL Division
555 Booth Street
Ottawa, Ontario
K1A 0G1
CANADA

MICROMEDIA

43 pp

DATE: September 23, 1991

92-06293/

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SUMMARY I

The Polish energy production industry is based almost entirely on coal and the disposal of wastes from power stations has caused growing environmental concern.

To alleviate this problem Polish academic scientists and engineers from the power and mining industries have developed a new method of disposal of power industry waste, whereby fly ash is mixed with water to make dense suspensions, AWDS, to which other wastes can be added. These suspensions remain fluid for several days and can then be pumped and transported hydraulically, but afterwards set to form a solid, virtually without the separation of water. The solid resembles soft rock, and its permeability to water and gases is low.

AWDS can either be dumped in landfill sites, which automatically become sealed against leakage and which, when full, can be readily reclaimed, or even better, AWDS can be pumped underground and used as stowing material for underground voids left after coal or mineral extraction. More sophisticated applications have also been developed.

The AWDS method has been successfully used in Poland, on an industrial scale, since 1983 and the number of sites at which it is employed is increasing. At present about one-sixth of power industry wastes produced in the industrialised Silesia region is treated.

The AWDS method has not, as yet been used for FBC wastes, since there are no large FBC installations in the country. It is highly probable that the method would work - a few relatively simple tests could demonstrate whether the method is feasible and if so, further research and development work could be planned and undertaken, on the basis of the considerable body of knowledge and experience which already exists. This should make prompt commercialization of combined FBC/AWDS technologies possible.

SOMMAIRE

L'industrie polonaise de production énergétique est basée principalement sur le charbon. Les problèmes que suscite l'élimination des déchets provenant des centrales énergétiques sont une source grandissante de préoccupations environnementales.

Pour résoudre le problème, les scientifiques et ingénieurs polonais oeuvrant au sein des industries minière et énergétique ont mis au point une nouvelle technique. Elle consiste à mélanger les cendres volantes avec de l'eau, de façon à obtenir une suspension dense (AWDS) à laquelle d'autres déchets peuvent être ajoutés. La suspension demeure à l'état fluide pendant plusieurs jours et peut être acheminée à un endroit particulier par pompage hydraulique et passe ensuite à l'état solide. Le produit solide ressemble à de la roche tendre et est peu perméable à l'eau et aux gaz.

Le produit solide peut être déchargé dans des emplacements à des fins de remblayage. Les emplacements deviennent forcément étanches et lorsque comblés, peuvent être réutilisés. On peut également pomper la produit dans la couche souterraine et l'utiliser comme remblai pour remplir les vides résultant de l'extraction du charbon ou de l'exploitation minière. Des applications plus complexes du mélange ont également été mises au point.

Depuis 1983, la technique AWDS a été utilisée à l'échelle industrielle avec succès en Pologne. Le nombre d'emplacements où elle est utilisée ne cesse d'augmenter. À l'heure actuelle, le traitement est appliqué à environ un sixième des déchets produits par les centrales énergétiques de la Silésie, région industrialisée de la Pologne.

La technique AWDS n'a pas encore été utilisée pour le traitement des déchets produits par la combustion en lit fluidisé (CLF) car la Pologne ne possède pas de grandes installations de CLF. Toutefois, il est fort probable que la technique serait utile; quelques simples essais de faisabilité pourraient en effet démontrer si elle peut être utilisée et dans l'affirmative, des travaux de recherche et de développement poussés, fondés sur les connaissances et l'expérience acquises antérieurement pourraient être entrepris. Ces travaux permettraient de commercialiser rapidement les techniques combinées CLF/AWDS.

I. INTRODUCTION

Interest in the safe disposal of power stations wastes in Poland and in particular, the possibility of placing such wastes in mine workings dates back to the seventies. The group at the Academy of Mining and Metallurgy (AGH) in Cracow was then active in this field, but real progress became possible after about 1980, when researchers from the Technical University of Silesia (PS) at Gliwice working in association with the South Regional Power Board (ZEOP), Katowice, showed that concentrated fly ash + water mixtures, with ash to water ratios between 1:1 and 3:1, after suitably energetic mixing gave long-lived dense suspensions. These dense suspensions of ash in water, which will be referred to here as AWDS, but have been called "slurries" or "emulsions", behaved like thixotropic non-Newtonian fluids, which made pumping and hydraulic transport possible, and after a time from several hours to some days would set, virtually without the separation of water, to a solid rather like soft rock. The PS group then concentrated on the methods of producing and pumping AWDS and patented them, mostly with various people connected with the energy industry, with the patent rights usually assigned to ZEOP, an institution which no longer exists. Meanwhile the AGH group of mining engineers, which represented considerable expertise in mine backfill, took up the subject of AWDS, published work on their physico-chemical and mechanical properties and investigated their possible uses in underground mining, including the stowing of old mine workings. They took out one patent on the filling of underground voids, in addition to the one they already held on mine backfill, both patents being granted by AGH.

The first industrial scale application of the AWDS technology of power station ash disposal took place in 1983 at the 'General Zawadzki' coal mine (now called 'Paryz')* in Dabrowa Gornicza, Silesia. AWDS was also pumped into an old open cast mine site nearby, 'Brzozowica'. The fly ash came from and the AWDS was prepared at the 'Lagisza' power station in Bedzin. It appears that at 'Lagisza' the design of the AWDS plant was to the credit of the PS/ZEOP group, while at the mine the mine engineers worked with the AGH people. Detailed accounts of the work at the mine were published.

After successful industrial scale tests at the 'Gen. Zawadzki' mine, the AWDS technology was taken up by a number of institutions connected with the Polish power and coal mining industries and many coal mines became interested.

In this report an attempt will be made to present briefly the development of AWDS technology in Poland, its present status, and to describe the properties of AWDS on the basis of:

- published literature (much of the story can be pieced together using literature sources only)
- patent descriptions
- interviews with power station and mine engineers and the research people involved
- site visits

* Many of the mines have now changed their names. To avoid confusion, when written records are referred to, the old names will be used.

II. DEVELOPMENT OF METHODS OF USING FLYASH IN UNDERGROUND MINING

In Poland, interest in the utilization of power station wastes, particularly fly ash, in mining practice dates back to before 1970, though the earliest papers contain little useful information. Most of them just comment on the desirability of developing a method of using bulk wastes produced by the power industry underground, where the coal originally came from.

In the 70's mining engineers from the Academy of Mining and Metallurgy (AGH) in Cracow published a number of papers concerned with the stowing of underground voids with mixtures containing power station wastes. It should be noted that in some of these publications (e.g. 16, 17) early American work was mentioned (Magnuson M.O., Malenka W.T., Bureau of Mines, 1970, Report of Investigation No. 8488), as well as work in France and in Czechoslovakia.

About the same time Polish copper ore mining industry engineers were working on self-setting mine backfill and filed patent applications and a number of other institutions concerned with the power and mining industries were also interested in various solidifying mixtures for mining applications, such as fly ash and portland cement with $NH_4H_2PO_4$ [8], flyash and gypsum with NaH_2PO_4 [9] or flyash and phospho-gypsum with NaH_2PO_4 [10]. A number of patents were obtained for compositions containing in addition to ash and water, water glass wastes from cement production, post flotation wastes, $MgCl_2$ and lime.

In some early technical scale tests on the filling of shallow voids [11], the voids were stowed with dry fly ash to which water was added "in situ". The mixture was reported to harden with time and the optimum proportion of water was given as 30%. In a 1976 patent a similar method is described, with 25% water recommended.

More rapid progress became possible after about 1980 and development work proceeded, mainly at the South Regional Power Board (ZEOP), Katowice and the Technical University of Silesia (PS), Gliwice and was associated with the names of Mr. J. Kmiecik and Dr. J. Rokita. In the course of this work it was established that concentrated ash-water mixtures, containing more that 50% by weight of fine fly ash from power station ESP's, had, after dynamic mixing, the properties of a non-

Newtonian fluid and remained liquid with very little or no water separation until becoming plastic and then setting to a solid with the consistency rather like that of a soft rock. The long-lived, self-setting dense suspensions of ash in water were often called "emulsion", (the technical jargon "emulgate" was used in Polish), but in this report will be referred to as AWDS.

The AGH group, headed by Dr. Ropski and including Dr. Mazurkiewicz and Mr. Piotrowski, were quick in realizing the potential of AWDS not only as a stowing material for underground voids, but also for a number of more specialized applications in underground mining. Studies on the physico-chemical and mechanical properties of AWDS, both in the fluid and in the solidified forms were carried out and papers [18, 19, 37-39, 42] and review articles were published [e.g. 21, 39, 40]. R&D work was also carried out under various contracts (Technical Reports, unpublished work) and the members of the group were involved in the first underground technical scale ('Jaworzno' mine [2, 47], demonstrations and industrial scale demonstrations ('Gen. Zawadzki' mine [2], of the new technology. The tests in the 'General Zawadzki' mine took place in October 1983 and a detailed account has been published [2]. AGH also obtained a patent on the filling of underground voids, using a self-setting mixture of 1 to 3 parts of fly ash to 1 part of water or saline water (at the time, salt mines were showing interest in the process [17, 21, 29]), which could also contain up to 40% of any solid, e.g. crushed slag (power plant bottom ash).

While the AGH group concentrated on the possible underground uses of AWDS, Dr. Rokita and others associated with PS and ZEOP and other institutions connected with the energy industry continued work on its preparation, pumping and transport and took a strong interest in the surface deposition of power station wastes. They filed more patent applications with various partners, mostly associated with the energy industry on the lining and sealing of landfill sites, storage tanks for AWDS or similar materials and the "thickening" of AWDS. One of their latest ideas, on a system for producing AWDS continuously also has recently been patented in Canada. In addition, they published a number of papers [30-36] and tried to popularise their methods abroad [32, 34, 36, 46].

After successful technical and industrial scale tests, the AWDS method has been in continuous use at the 'Gen. Zawadzki' mine, where much of the fly ash from the nearby 'Lagisza' power station is now used for backfilling old workings. The method has also been taken up by other mines, e.g. 'Brzeszcze' [43], some have also developed their own versions of the method, so as to get around the existing patents.

Interest in the process has been shown abroad and a number of developments have taken place ([21]); in Yugoslavia, Germany and Hungary.

III. THE 'LAGISZA' POWER STATION - 'GEN. ZAWADZKI' COAL MINE ASH DISPOSAL SYSTEM

The information contained in this chapter relates to AWDS produced at the installation situated at the 'Lagisza' power station in Bedzin and stowed inside the 'Paryz' mine, partly in the 'Grodziec' mine and, until recently, also dumped in the nearby 'Brzozowica' landfill site. The power station has no proper dumping site for its wastes and practically all the fly ash is treated as described below.

The AWDS installation at 'Lagisza' power station and the 1983 industrial scale underground tests

The AWDS installation at 'Lagisza' corresponds essentially to publications by Rokita [30] and Rokita and Tomaszewski [32], all including the same schematic diagram, shown in **Fig. 1**. The fly ash from the power station ESP's are collected in storage bins. Weighed batches of the ash are fed into the mixer, where the correct quantity of water is added (the patent specifies a mass ratio of 1:1 to 3:1, but a ratio of about 2:1 is actually used) and the mixture is stirred. The mixing step is important and must be sufficiently energetic to produce a long - lived suspension, which then flows into a retention tank, where it is kept agitated by compressed air bubbles. From the retention tank, AWDS can be pumped to the dumping or stowing site, as required. Slag (bottom ash) can in principle be added to AWDS, but this is apparently not done often. A photograph of the outside of the installation at Lagisza appears in ref. [32].

A schematic representation of the original arrangement of transport lines and the locations of the mine and surface dumping sites appeared in the 1984 account of the first industrial scale underground tests [2] and is reproduced in **Fig. 2.** A steel pipeline, 150mm in diameter and 1200m long conveyed the AWDS to a pipeline junction, from where it could either be pumped for another 300m to the 'Brzozowica' landfill site, an old open cast coal mine, or for 1410m to a retention tank by the side of the backfill shaft 'Walery', belonging to the 'Gen. Zawadzki' mine. The 'Brzozowica' site was officially closed in January 1991 and the pipeline outlet is now blocked. During the 1983 tests [2] AWDS from the retention tank was fed through the mine shaft down a 185mm pipe, which dropped vertically 80m and continued horizontally underground for another 240m. In the test the intention was to stow a 24m length of a dip heading (marked 11 in Figs. 2 and 3) in coal seam 501. Arrangements were made for observations to be made along the whole of the length of the heading. The process was carried out in three stages using a total of 620m^3 of AWDS, with the ash to water ratio equal to about 2.5 : 1, at a mean feed rate of 180m^3/h. After 24 hours the AWDS had a plastic consistency and there were a few centimetres of water on the surface. This water gradually disappeared and after 4 days the mass became solid. The compressibility of the solidified material under a standard stress of 15 kN/m^2 [16] was about 10%, the compressive strength about 100 N/cm^2 and water permeability coefficient was 2.5 x 10^{-6}m/s, so that the material was described as practically impervious to water. No gas evolution was observed and thermal effects were not mentioned. It was stressed, however, that because of the

fluid consistency of the fresh AWDS, care had to be taken to contain it in the stowed area by suitable stopping, constructed of timber, with additional layers of brattice cloth. The need for controlling the flow of fresh AWDS was also stressed in other, later publications, e.g. [21, 39] - typical wooden frame stopping with brattice cloth is insufficient and AWDS may seep through. The authors of reference [39] recommend the use of mixed timber-masonry stopping or double wooden frame stopping with brattice or ventilation cloth, with the intervening space packed with sand, gypsum or AWDS itself.

AWDS stowing inside the 'Gen. Zawadzki' mine after 1983

Since 1983, the 'Gen. Zawadzki' mine has been using AWDS on a regular basis. An account of the work carried out up to 1988 has been given by Ropeki and Piotrowski [39]. 3500m of no longer needed dip headings were filled with AWDS, which made it possible to isolate completely, for ventilation purposes, the active headings from old workings in coal seams 501 and 816. This is illustrated in **Figs. 3** and **4**, reproduced from [39]. All the dip headings were sloping at more than 5° and stowing them was a simple matter. Problems were encountered only with the filling of the 1a dip heading and the water heading in seam 501, because of water seeping in at a rate of 50 l/min. The water diluted the AWDS, which then lost its ability to set and it was necessary to make provision for drainage, which would not normally be required.

Old workings with roof collapse have also been filled in - longwall 1, seam 816, with the simultaneous filling of adjacent headings. During this particular operation the ability of AWDS to penetrate into cracks and crevices in the rock mass was clearly demonstrated. The amount of AWDS stowing material supplied, 36 310 tons, containing 24 009 tons of dry flyash, exceeded earlier estimates of the capacity of the workings by a factor of two.

Attempts have been made to use AWDS for stowing workings behind the active longwall 605 in seam 816, coal being extracted mechanically with roof collapse. AWDS was brought to the area through a pipeline laid along the floor of gallery +40 and dip headings 13, 7a (Fig. 4). Because the longwall lay above the active 390m level, stopping had to be constructed at the lower end of dip heading 13 and between headings 7a and 7. In order to prevent penetration by AWDS, double timber frames covered with wooden boards and lined with several layers of ventilation cloth were used. In the intervening space a gypsum "plug" was made. In addition, arrangements had to be made for drainage of natural water flow. This was effected by using a 100mm pipe passing through the stopping. The construction of the stopping is illustrated in **Fig.5**. AWDS was fed in stages, a week apart, to allow the material to harden, until a plug was formed in dip heading 13. Afterwards, spaces beyond the plug could be filled continuously.

It appears, however, that at present AWDS is placed mostly in old workings. One of the disadvantages of getting too close to active longwalls is that the vibration generated by operating mining machinery slows down the setting of AWDS ([47]).

The 'Brzozowica' landfill site

This is the site of an opencast mine, where there had been an outcropping of coal seam 501. The mine was active in 1955-61. Detailed records of the extent of the excavations are difficult to obtain now, but the depth must have been at least 25m. After mining operations were over, the pit was used for depositing mine waste, rubble, etc. The deposition of AWDS took place from about 1983 until the end of 1990, without records being kept on how much was in fact was dumped. In January 1991 the mine authorities closed the site to further dumping of AWDS, but there is evidence that although the pipeline was blocked, loads of AWDS were dumped, probably from concrete mixer trucks. The solidified material is a grey mass, and it is possible to walk on the surface of it. The consistency varies between something like soil and moist sand, on which one leaves very shallow footprints. There is no wind-blown dust. At one time metallurgical industry wastes, regarded as hazardous, were buried at the site, sealed between layers of AWDS. No records appeared to be available concerning any leaching from the site. Older parts of the site are already covered with scrub, and plants are beginning to establish themselves where the surface is probably no more than 1 -2 years old.

The effect of mine geology and mining conditions on the feasibility of using the AWDS technology for mine backfill

The effect of geological and mining conditions will be considered with particular reference to the 'Gen. Zawadzki' coal mine, but the conclusions can be generalised and are confirmed by literature data for other coal mines.

The 'Gen. Zawadzki' mine has been using AWDS for:
- stowing old workings in seam 510
- backfilling no longer needed headings in seams 501 and 816
- stowing active workings with roof collapse in seam 816

The relevant features of the geological and mining conditions can be described as follows:

a) <u>Depth of the stowed workings.</u> In the 'Gen. Zawadzki' mine the workings in seam 510 being backfilled are shallow, situated in the vicinity of an outcropping of the seam. Those in seam 501 lie at a depth of 250-280m and those in seam 816 at depths of 250 and 300m. This is not particularly important, because the mining safety conditions had to be taken into account at the exploitation stage, and the problems associated with the use of AWDS are connected with selecting the

appropriate technical solution (feeding in AWDS through pipelines passing boreholes, laid along headings, etc).

b) Fault lines and faults. The faults present in the mine area ('Koszelewski', 'Paryzki' - see Figs. 3 and 4), are either avoided in the course of the mining operations, or appropriate measures are taken during the preparation of mining operations and the operations themselves. They are thus unimportant from the point of view of AWDS technology.

c) Sloping of the coal seams. The dip angles range from about 15° for seams 501 and 510 to 0-30° for seam 816. This has to be taken into account when using AWDS (for information on the placement of backfill pipelines, forced transport, the construction of stopping).

d) The thickness of the coal seams. The thickness of the seams mined is not particularly relevant. In the case of the thick seams, 501 and 510 (Fig.6), coal is mined mechanically, layer by layer downwards, with roof collapse, the rubble being consolidated using AWDS, to form an artificial roof [14, 21].

e) Rock strata forming the roof and floor of the coal seams mined. At the 'Gen Zawadzki' mine AWDS is used where the roof and the floor consist of sandstone (seams 501, 510) and claystone (seam 816) - see Fig.6. Any problems associated with the presence of these rocks have to be solved at the coal extraction stage. It should be noted, however, that the structure of the rock mass may have an effect on the AWDS holding capacity of workings, but, as mentioned above, so far it has not been possible to arrive at any generalisations. Estimates can be wrong by as much as a factor of two ([21, 39],).

f) The hydrogeology of the mine. The 'Gen. Zawadzki' mine suffers from problems associated with the presence of underground waters and constant water seepage into workings. In the course of coal extraction from seam 816, there is a need for constructing water reservoirs. The presence of water must be taken into account in the construction of stopping [39], as mentioned above, and it must be borne in mind that fresh AWDS can be diluted with water, while the solidified material is practically impermeable [18, 24, 29]. With suitable stopping and draining, AWDS has been used to fill a water reservoir in seam 816 workings (Fig.4, and ref. [39]).

g) Coal mining method. Seam 816 is mined mechanically, with mechanical supports, using the longwall method, with roof collapse. The breath of the longwall is about 100m, the height, 2.5 - 3.5m.

h) Surface deformation. When AWDS is used instead of conventional hydraulic (sand) backfill, surface deformation and the degree of subsidence is no greater and may even be reduced. This problem has been discussed in detail in [21], with reference to a number of specific cases.

i) Conclusions. The almost complete lack of a connection between the geological and mining conditions and the use of the AWDS technology in the 'Gen. Zawadzki' mine is due to the fact that backfilling constitutes the final stage of mining operations. Difficulties and hazards associated with geological and mining conditions are encountered and have to be dealt with at this stage of preparing for coal extraction and during mining operations.

IV. PREPARATION, TRANSPORT AND DEPOSITION OF AWDS

Preparation of AWDS

As mentioned above, at the 'Lagisza' power station practically all the fly ash is turned into AWDS at the site, using the technology described under [30, 32]. The ash is mixed with water in batches, with intensive stirring for about 2.5 min. The AWDS is then discharged into a retention tank, the discharge process taking 0.5 min. The duration of the whole cycle is about 3.5 min. and 6 - 8m^3 of AWDS is made at a time. The retention time in the tank is in the order of 15 min., and air is bubbled through the mixture to maintain agitation and prevent any solidification. Pumping from the retention tank is continuous. The quantity of fly ash processed is about 2 - 3 thousand tons per day. The amount of ash processed annually over the 1986-88 period was 60 - 65 thousand tons [6], the total for 1990 was about 90 thousand tons and in 1991 this figure should be exceeded.

No similar AWDS plant is reported to exist yet at any power station (one is being built, at Opole, and others are said to be planned), sometimes AWDS is prepared near backfill mineshaft [40]. A schematic diagram of the installation at the 'Brzeszcze' mine is provided in the paper reference 4 which gives an account of this development [43] and help from the AGH people is acknowledged. AWDS is pumped directly underground through the backfill pipeline system. At the 'Bobrek' mine the method used appears to be something between the AWDS technology and traditional hydraulic backfill [41], flyash being, in effect "washed down".

In some cases, particularly at the 'Boleslaw Smialy' mine, considerable quantities of fly ash are stowed [e.g. 4, 5], though this can hardly be classified as the same technology, because the dry ash is stowed inside mine workings and then wetted underground, with somewhat similar final result - backfill hardening with time [11, 15].

Some improvements and modifications to the AWDS plant design have been proposed by Dr. Rokita and associates. Thus, patent describes a method of preparing AWDS by adding more fly ash to a thinner slurry and the most recent patent description proposes that AWDS should be made in a continuous process. There is, however, no evidence of these methods having yet been used in practice.

There are very few data relating to side effects associated with the preparation of AWDS. Thermal effects with ash and water alone are very small, but have been studied for backfill mixture made up of flyash and gypsum, in mass proportions 30:70 and 50:50, with NaH_2PO_4 added. Temperature increases were found to be much less with the higher ash proportion. Dr. Rokita has mentioned having seen some Russian data, where mixtures with a higher CaO content made the temperature rise by about 50°C.

The evolution of small quantities of gases during AWDS preparation is mentioned only in [38]. CO and CO_2 were detected in the early stages and it was concluded that this was due to the adsorption of components of the flue gas on fly ash particles. With fly ash from 'Lagisza' there was also the smell of ammonia, but no attempt was made to account for its presence.

Transport, AWDS and fly ash

The AWDS preparation plant at 'Lagisza' is situated at the power station site and so the question of ash transport is not a vital one, because the 'Paryz' mine, where most of the ash is stowed, is only a few kilometers away and pipeline transport is the obvious answer. The layout of the system [2] has already been described in Chapter III. According to engineers at the power station and the mine, AWDS is sent to the mine during two shifts. Some is also taken in concrete mixer trucks to the 'Grodziec' mine, not far away, (no quantities have been indicated and there is no published data relating to this mine) and sometimes to the 'Myslowice' mine [22]. Some dumping at the 'Brzozowica' landfill site may also still take place. When AWDS is ready to be pumped, a telephone message is sent to the mine (it is important that the stowing site should be made ready to receive AWDS through the construction of stopping etc.) and to men at the 'Walery' backfill shaft, who operate the auxiliary pump and valves (Fig.2). The discharge of AWDS takes place at a rate such as to maintain a flow rate in the pipeline at which there is no sedimentation [34], the average linear velocity being close to 1.5 - 2 m/s (Chapter VI). When the backfill cycle is over, all the pipelines, etc. must be flushed with water, so that they do not become blocked with solidifying AWDS and can be ready for the next cycle.

The theoretical problems associated with the pumping and hydraulic transport of AWDS have been considered in a number of publications, particularly those association with the name of Dr. Rokita. The properties of AWDS relevant to hydraulic transport have been investigated and the results obtained for ash from a

number of sources and for different ash to water mass ratios are available. Further information with references is presented in Chapter VI.

The problem of pipeline transport distance has been considered by Dr. Mazurkiewicz [21], who tried to develop relationships which could provide practical guidelines. He produced a number of semi-empirical formulae, taking into account the presence of bends in the pipeline and gradients but with a very limited range of available data relating to this problem, the error margins had to be rather wide. At the 'Paryz' mine the total length of underground backfill pipelines is now about 5 km and in some cases AWDS can be made to flow uphill. Dr. Rokita, who has specialised in pumping and hydraulic transport, is of the opinion that pipeline transport for up to 10-12km is possible, without gravitational augmentation and with one pump only, after the mixing stage.

When the dry fly ash is transported in bulk by rail, it is carried in cement cars [12] or open cars and has to be heavily sprinkled with water to keep down dust [5, 14]. When smaller quantities are involved, transport is by road, using trucks adapted for carrying cement [4].

The placement and dumping of AWDS

Some of the problems which can be encountered during the stowing of underground voids with AWDS have already been mentioned in connection with the 'Paryz' mine. In Chapters III and V more will be said about the various possible uses of AWDS in mining practice.

As to dumping in open landfill sites, 'Brzozowica' remains the only site of any size where this has been done. According to Mr. J. Kmiecik, in the mid-eighties the site was something of a showpiece, to advertise and popularise the method, but its present state gives little idea of what a well-managed site should look like. Another site (an old limestone and marl quarry) is now being prepared, at Groszowice near Opole, where AWDS produced at a heating plant, using the 'Lagisza' installation design will be dumped, starting probably with the 1991/92 heating season.

The options which can and have been used in the preparation, transport and placement of AWDS are represented schematically in **Fig. 7.**

Problems, breakdowns, wear of the installations

Some of the problems which can be encountered in mines have already been mentioned - e.g. the effect of underground water. Detailed discussions of these are outside the scope of this report, but data are available in publications [e.g. 21, 38, 39].

As to problems associated with the preparation and transport of AWDS, in 1985 at 'Lagisza', something went wrong (probably the mixing) and both pipelines, leading to the 'Brzozowica' site and to the 'Walery' shaft were blocked (as already mentioned, the pipelines are flushed after the completion of each cycle). Efforts are continuing in the direction of ensuring that the properties of AWDS are kept constant.

According to the mine engineers, the wear problems are similar to those experienced with conventional hydraulic backfill. Dr. Rokita and associates have considered the problem of pipeline erosion and conclude that there is an ash to water ratio for which these problems are at a minimum (Chapter VI).

V. AWDS IN UNDERGROUND MINING

Because of the solidification of AWDS and its favourable physical properties (Chapter VI), in addition to its bulk use for the stowing of mine workings, smaller quantities can be used in underground mines for a variety of purposes. These will be mentioned only briefly.

This subject has recently been reviewed [21, 39, 40]. The present account follows from these reviews. Detailed accounts are available in the literature.

When the use of AWDS is considered, the conditions inside the mine must be carefully examined, both from the point of view of geology and mining engineering. These conditions can vary enormously and it is rather useless to try to generalise [21, 40,].

Basically, AWDS can be used in two ways, the filling in of post-exploitation underground voids, such as headings or voids present in rubble after roof collapse, or for the isolation of old workings and sealing the rock mass, and this can be done for a number of different purposes. Fig. 8 is an attempt at representing this schematically.

The filling of post exploitation voids

1. Rubble consolidation after roof collapse. This method has been used mainly in connection with stowing old workings, as at 'Gen. Zawadzki' mine and several others [39]. AWDS penetrates into all spaces, including the cracks and crevices in the rock mass and solidifies. The compressibility of the consolidated rubble is reduced [39], which may help to reduce surface deformation and subsidence in mining areas [21]. The consolidation method has also been used for active longwalls (see Chapter III) and in connection with the mining of thick coal seams, working layer by layer downwards, when AWDS was used for creating an artificial roof out of rock rubble [21, 44].

2. Filling of shallow voids. This is particularly useful if the voids are under built-up areas [21, 39] and buildings are threatened by subsidence. It has been used at several localities [21].

3. Filling of old dip headings. Old dip headings were stowed at the 'Gen. Zawadzki' mine (Chapter III) [39, 41] with an improvement in mine ventilation.

Isolation of old workings, sealing the rock mass

The fact that the solidified AWDS has a low water and gas permeability can be taken advantage of to improve mine safety conditions; to reduce the evolution of methane into workings and increase its recovery. It has been mentioned that AWDS can be used to contain underground water flow and to seal underground water reservoirs. It has also been employed at the 'Myslowice' mine to isolate an area in which fire had broken out [39].

Other applications that can be mentioned here, though minor in terms of the quantities of AWDS used, are filling in voids behind lining and the construction of stopping and of "plugs" [1, 22].

VI. THE PHYSICO-CHEMICAL AND MECHANICAL PROPERTIES OF AWDS

After the self-setting properties of concentrated ash-water mixtures became known, interest in their properties increased and papers were published, giving accounts of various laboratory studies that were carried out.

Dr. Rokita and associates were primarily interested in those properties of AWDS that had a bearing on pumping and pipeline transport and on materials of construction and also those that made the dumping of it in landfill sites an attractive proposition.

Workers associated with AGH investigated the mechanical strength of solidified AWDS derived from various ashes and their permeability to water, since their primary interest was to use this material in underground mines.

The chemical composition of fly ash

The chemical composition of fly ash obtained from Polish power stations is probably fairly typical of the material collected on ESPs when hard coal is burned in conventional pulverised fuel furnaces. The concentrations of the main components from various sources vary to a degree that might be expected [8, 23, 39]. The concentration ranges given for the main ash components in [34] are even wider: SiO_2 - 43-57%; Al_2O_3 - 18-23%; Fe_2O_3 - 7-16%; CaO - 4-11%; MgO - 1-5%; SO_3 -0.5-

3.5%. For 'Lagisza' fly ash the CaO content has been given as 3.65% in 1980 [8], 6.12% in 1988 [39] and our own figure for fresh samples collected in June 1991 is 3.6%. This clearly reflects the variability of the coal burned.

The size distribution of fly ash.

Fly ash particle size distribution data can be found in several publications, for fly ash from a number of sources [8, 9, 16, 17, 23, 34, 39]. The size distribution curve reproduced from [39] is shown in **Fig. 9.** According to [34] the fine fractions, below 75μm, may account for 70-95% of typical fly ash and the proportion of the finest particles, below 20μm, is most variable.

The physical properties of AWDS and of the solidified material

The properties of AWDS which are important for its use in underground mining and clearly also if it were to be dumped in landfill sites have recently been listed and discussed by Mazurkiewicz [21]. He begins by stating that there is a problem in the selection of reference criteria and standards - e.g. should the solidified AWDS be treated as natural rock or an artificial solidified material, such as concrete? There is, as yet, no uniformity of approach. Also, the tests specified by Polish Mining Industry Regulations for mine backfill material, formulated for traditional (sand) hydraulic backfill (BN 77/0441-01) are not only inappropriate but also very crude.

The present discussion follows closely that in [21], but other data are also included.

Fly ash to water ratio. Patents specify more than 1:1, between 1:1 and 3:1. Ref. [21] states that the ratio may range from 1:1 to 4:1, the lower limit corresponding to most dilute mixtures with no sedimentation, the upper one to the mass becoming "plastic". The exact ratio depends, however, on the fly ash used. Data for different ashes are quoted in [39]. In practice an ash to water ratio close 2:1 is usually employed.

Mass concentration (solids loading). This is defined as the mass of solids present (including possibly other solids in addition to fly ash, as specified as a fraction of the total mass. This may range from 0.31 to 0.58. (N.B. in Dr. Rokita's publications [30, 32-34] the volume fraction, c_v has also been used).

Time to solidification. The time may vary between very wide limits for AWDS based on different ashes, from hours to many days [21], but about 2-4 days appears to be usual [19, 20, 29], which is confirmed by our own observations on flyash from the 'Lagisza' power station (see Chapter VII).

Compressive strength of the solidified material. This quantity has been studied many times [16, 17, 20, 23, 38, 39]. It depends very strongly on the ash used (though it would be difficult to see a correlation with e.g. the ash density, particle size distribution, specific surface or even chemical composition [39]), and the ash to water mass ratio. It increases with time after solidification and is greater if seasoning takes place under high humidity conditions [21]. In the majority of cases the compressive strength after 28 days should exceed 100 N/cm^2 and for some "active" ashes it might be higher by more than a factor of two. Data taken from [39] are shown in **Fig. 10.**

Density of AWDS. The range quoted in [21] is 1.20 - 1.88 Mg/m^3. The density of AWDS consisting of fly ash and water may be important only if other solids are to be added (as mentioned above) without the transport properties being affected. Typical relationships involving ash and AWDS densities, taken from [34] are illustrated in **Fig. 11.**

Apparent density after solidification. The apparent density, measured as for soils or rocks, ranges from 1.40 to 1.65 Mg/m^3 [21].

Supernatant water. This may appear after 3 - 6 hours and remain for days [21, 42]. The amount is often given in terms of the volume % of AWDS. For an ash : water ratio of about 2:1 it may be vary from practically nothing to about 10%, depending on the ash, and the mixing process [42]. A diagram illustrating the dependence of the amount of water above the solidifying AWDS on the volume fraction of fly ash [34] is reproduced in **Fig.12.** The gradual disappearance of water has been confirmed by us on AWDS samples originating from the 'Lagisza' power station and obtained from the 'Paryz' coal mine (Chapter VII). The disappearance of water as well as solidification can, according to literature data [38], be accelerated by the addition of small quantities of gypsum - e.g. with ash from the 'Leg' power/heating plant and with 2% of the ash replaced by the same amount of gypsum and at a solids to water ratio of 2:1 all water disappeared after 3 hours.

Compressibility. This is normally given as the change in volume, %, under a stress of 15 kN/cm^2 [16]. The values increase with increasing fly ash to water ratio and depend on the ash used. For solidified AWDS with an ash to water ratio of 2:1 the compressibility measured after 28 days of seasoning ranged from about 7% to just over 12% [38, 39].

Behaviour upon contact with water

Water permeability. For the solidified material, according to [21] the permeability coefficient should generally be less than 10^{-6}m/s, but for materials derived from different ashes and seasoned for 28 days values ranging from about $0.5x10^{-6}$ to $5.8x10^{-6}$ are quoted [39]. There is little doubt that the water and gas permeability of the solid is very low, and that the claims made that AWDS can be used for lining and sealing landfill sites, sealing rock masses in underground mines, [40] and even lining water conduits [24] are founded on a sound basis.

Leaching. The pH of water in contact with fly ash is slightly on the alkaline side [16] and some leaching must take place with AWDS. The problem has been investigated several times, to varying degrees of depth [13, 20, 24, 28, 39], but no results could be found on the long-term effects of dumping AWDS.

A laboratory study of the leaching process carried out [24] in connection with the possible use of fly ash for lining water conduits. The ions found in the leachate were mainly Ca^{2+} and SO_4^{2-}, as might have been expected.

The retention of saline water in solidified mine backfill, possibly "enriched" with gypsum has been considered as a method of reducing the amount of saline mine waters discharged into rivers. According to [29] the presence of NaCl aids the solidification process, but [13] suggests that some chloride ions would be leached out.

Sample "integrity". Fresh AWDS may easily become diluted with water, particularly if there is any agitation, but the solidified material shows different types of behaviour, ranging from crumbling immediately on contact with water to remaining apparently unaffected, with no signs of any tendency to revert to the original form. Our own observations were made on samples of material that had been solidified since 1983. A cube cut from it retained its shape after being kept under water for a month (Chapter VII).

The rheological properties of AWDS

The properties of AWDS relevant to its pipeline transport are important and have been considered in many publications [21, 29-31, 33, 34, 36 and 42]. Extensive laboratory studies have been carried out, but the value of the correlations derived [42] may be questionable.

Fresh AWDS has the properties of a non-Newtonian fluid and the relationships and data given by Rokita and Tomaszewski [34] are probably most illustrative. The behaviour of dilute suspensions of fly ash in water (solids volume fraction, c_v, below 0.15) is described by Newton's equation,

$$\tau = \mu \, du/dy$$

where τ - shearing stress
μ - dynamic viscosity
du/dy - velocity gradient (shear rate)

At higher ash concentrations beyond $c_v = 0.15 - 0.20$, the suspension obey the equation of Bingham,

$$\tau = \tau_o + \mu_{p1} \, du/dy$$

where τ_o - threshold stress for non-Newtonian behaviour
μ_{p1} - plasticity coefficient of the mixture.

The values of these quantities depend on the proportion of fly ash present, as illustrated in **Fig. 13.**

Other quantities relevant to pipeline transport, discussed in the same publication [34], and also mentioned elsewhere [21, 25] are the critical velocity for turbulent flow in pipelines, below which sedimentation might occur, energy loss per unit mass of ash transported, energy required for pumping a unit volume of AWDS through a pipeline and relative wear of the installations. All these are all represented in **Fig. 14**, after [34], as functions of the volumetric fly ash concentration.

VII. ANALYSIS OF AND OBSERVATIONS ON SAMPLES OF FLY ASH AND AWDS

In the course of the site visits, the following samples were collected:

A. Fly ash, from the 'Lagisza' power station, taken from ash storage bins.
B. AWDS, from the 'Lagisza' power station, freshly prepared, as a part of a demonstration of the ash treatment plant.
C. AWDS, from the 'Paryz' coal mine, taken from the stowing site and still fluid.
D. Solidified material (lumps), from the 'Paryz' mine, formed from AWDS which had been deposited inside the mine in 1983.

PHYSICAL CHARACTERISTICS OF THE SAMPLES

Appearance:

A - apparently homogeneous, grey, fine powder
B, C - grey coloured suspension, fully fluid
D - solid, dark grey lumps, rather like soft rock

A. Dry fly ash

Bulk density (mean for 6 samples)	-	988 kg/m^3
Combustibles	-	1.52%
Sieve analysis	-	90% of the material below 250 μm
		50% " " " " 200 μm

The particles size distribution is similar to that for "bottom ash" from a CFBC pilot-plant using Nova Scotia coal and limestone (data supplied by Dr. E.J. Anthony, August 1991).

CHEMICAL ANALYSIS

Samples A, (B had to have the same composition and C had to be very similar) and D were analysed for the main components, particular attention being paid to the CaO and sulphate content. The results were unremarkable, in that they were typical of fly ash (Chapter VI), though there was an appreciable difference between samples A and D, which contained a mean of about 3.6 and 6.2% CaO, respectively. D also contained much more unburnt carbon, over 8% as compared with about 1.5% in A, which probably accounts for the dark colour of the D samples. It should be noted that 'Lagisza' ash in 1980 [8] and in 1988 [39] was reported to have contained 3.65 and 6.12% CaO respectively, which confirms the variability of the ash. Sulphates were lower in A than in D, but the Ca/S ratio was similar at about 5. Chlorides were very low in A and low in C and D. Since they clearly came from the water used to make the AWDS at 'Lagisza', they were not determined quantitatively.

THE WATER CONTENT OF THE SAMPLES

3 to 5 samples of B, C and D were dried in constant mass at 105°C

Material	Mean mass loss, %	Comments
B	19-43	mixture not homogeneous
C	24-25	material well mixed
D	21-22	the material appears solid

OTHER TESTS AND OBSERVATIONS OF THE SAMPLES

1. **B and C were kept in closed jars and the changes observed**

   After 2-3 days: - water appeared above, more with B; under the water the materials had the consistency of thick mud
   - the supernatant water, in addition to Ca^{2+} ions contained appreciable amounts of SO_4^{2+} and Cl^- ions (from the water used at 'Lagisza')

   After 10 weeks: - above B 90% of the water has gone
   - above C there is no water at all
   - both are hard

2. **Several 5 cm cubes were cut from D and tested, with the following results:**

   a. A cube dried at 105°C immersed in distilled water in 10 minutes took up to 4 - 6 cm^3 of water.

   b. A cube kept under water for 7 weeks retained its shape and took up only another 3 - 4% of water.

c. A cube that had been kept under water was dried at 105°C - the mass loss was about 25%.

d. The water in which the sample had been kept gave positive tests for Cl^- and SO_4^{2-} ions as well as Ca^{2+} ions

Conclusion: the "old" solidified material is resistant to the action of water and the solidification appears to be irreversible.

ADDITIONAL TEST ON OTHER MATERIALS

At about the same time the laboratory acquired, for other purposes, some samples of solids from a bubbling FBC (retrofit), in which desulphurisation had been used. The samples came from the bed (coarse particles, up to about 6mm) and from the preheater (?), cyclone and baghouse (fine particles). The mean CaO content of the samples was 4.3, 8.25, 9.61 and 11.55 respectively and the degree of conversion of the Ca to sulphate was very low for the bed material and of the order of 25 - 30% for the other samples. Mixtures of these solids were used to make up slurries with water, with and without added $Ca(OH)_2$. The fresh mixtures were of different consistencies, but they all solidified after being left in open containers for times from several days to about 3 weeks.

VIII. THE FEASIBILITY OF USING THE AWDS PROCESS FOR FBC WASTES

In the light of all the evidence presented in this report and derived from a variety of sources including site visits and interviews with people responsible for developing the method, there can be no doubt that the AWDS technology is very attractive for disposing of fly ash from conventional power stations. Most ashes, when mixed with water in the correct proportions do solidify as claimed in the patents.

Ash from CFBC will, however, be different in a number of respects and in particular, because of the use of desulphurisation, there may be as much as 20% of $CaSO_4$ present in the form of anhydrite, with variable amounts of free CaO. The particle size distribution may also be different, but the chemical composition might prove more important.

Solidifying composites made up of fly ash and gypsum has been described [9] and it has been mentioned that the addition of small quantities of gypsum to fly ash-water mixtures accelerates the setting of these mixtures [39]. A composition for sealing the base of surface or pit landfill sites has been patented, consisting of fly ash, $CaSO_3$ and $CaSO_4$ (from wet flue gas desulphurisation) and water, with the possible addition of $Ca(OH)_2$. Anhydrite is mentioned in patents, but they do not contain any really useful information. One can thus only speculate as to how FBC ash might behave if used to prepare AWDS.

The mixture would most probably set, possibly even more rapidly than the fly ash AWDS - and this seems to be supported by our very crude tests made with bubbling AFBC ash, mentioned in Chapter VII. The presence of coarser particles should not be an obstacle as Dr. Rokita maintains that his pumping system can cope with particles 10-60 mm suspended in AWDS and the patents do mention the addition of slag (bottom ash) to the AWDS.

Experiments, probably very simple ones to begin with, are needed to establish if CFBC wastes can be used to prepare AWDS. If so, more careful work would be required, both on physico-chemical and mechanical properties of FBC AWDS before environmentally acceptable methods of disposing and/or utilizing them could be proposed with full confidence.

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Fig.4. **The use of AWDS in seam 816, 'Gen. Zawadzki' coal mine** (reproduced from Ropski and Piotrowski [39])

Fig.5. **Stopping constructed in dip heading 13, seam 816, 'Gen. Zawadzki' coal mine** (reproduced from Ropski and Piotrowski [39])

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Fig.7. **Fly ash utilization in underground mines using the AWDS technology** (based on Ropski [40] but also including information from other sources [2, 6, 22, 25, 39, 40, 43])

Fig.8. **The utilization of AWDS in underground mines** (based mainly on [39, 40] and data from [1, 2, 6, 11, 14, 15, 22, 25, 41, 44])

Fig.9. **Particle size distribution for fly ash from different power stations** (reproduced from Ropski and Piotrowski [39])

Fig.10. **Compressive strength of solidified AWDS, change with seasoning time** (reproduced from Ropski and Piotrowski [39])

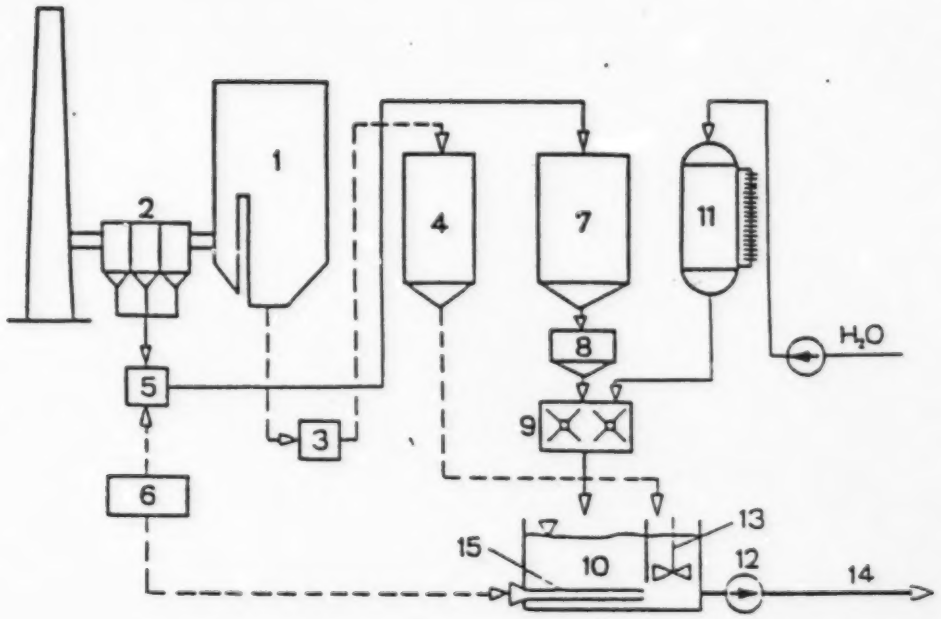
Fig.11. **Fly ash and AWDS - density and concentration relationships** (adapted from Rokita and Tomaszewski [34])

Fig.12. **Sedimentation behaviour of AWDS as a function of fly ash volume fraction** (adopted from Rokita and Tomaszewski [34])

Fig.13. **Rheological properties of AWDS as a function of the fly ash volume fraction** (adopted from Rokita and Tomaszewski [34])

Fig.14. **Quantities relevant to pipeline transport of AWDS, as functions of ash volume fraction** (adopted from Rokita and Tomaszewski [34])

Fig. 1. Installation for making a highly concentrated slurry of fly ash and water: 1-boiler. 2-ESP's. 3-stag breaker. 4-slag bunker. 5-pneumatic transport device. 6-air compressor station. 7-fly ash storage bin. 8-weighing batches. 9-mixer. 10-retention tank. 11-metering tank. 12-pump. 13-mixer. 14-slurry dumping. 15-air bubbler. (reproduced from Rokita and Tomaszewski [32]).



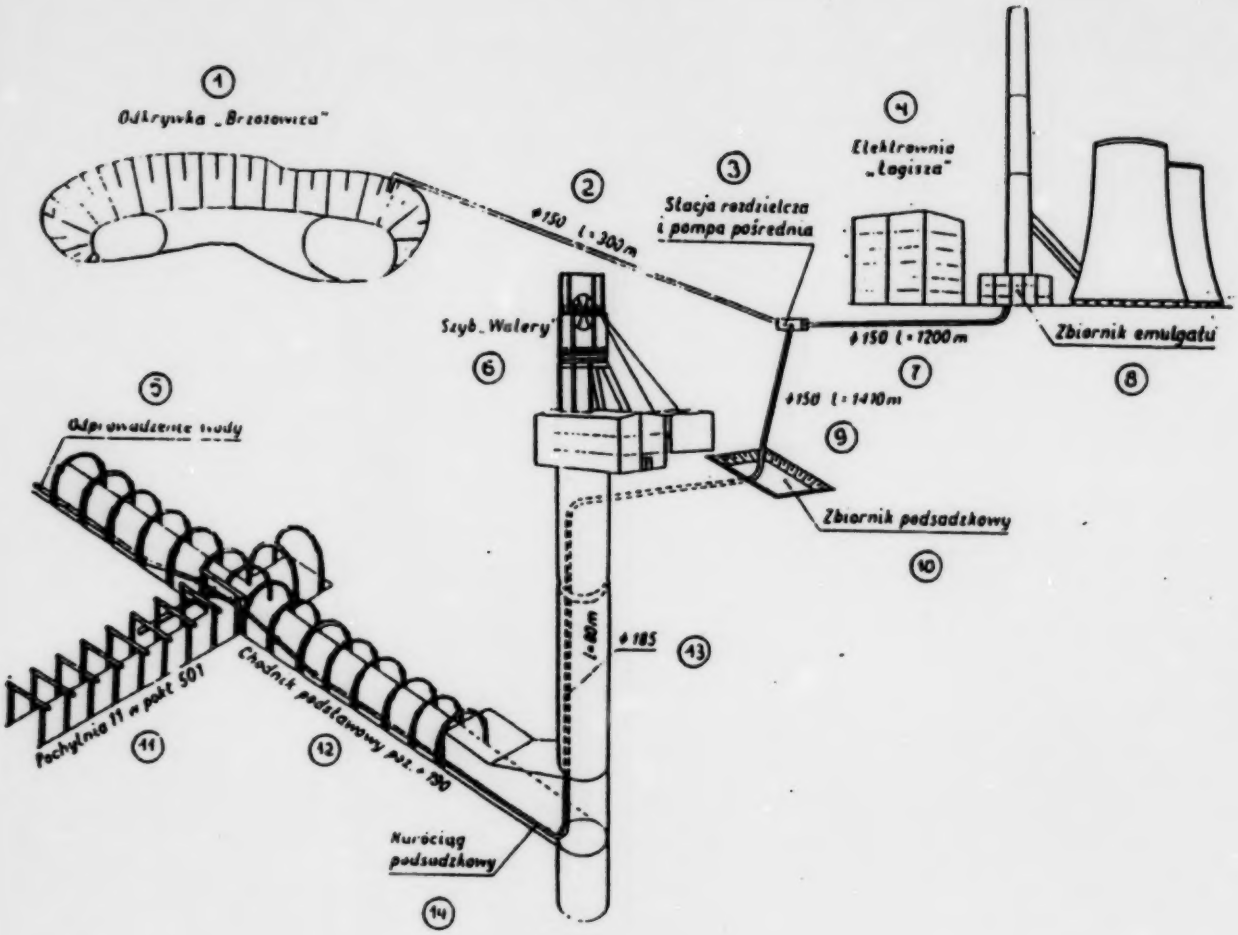


Fig. 2. The 'Lagisza' power station, the backfill mineshaft 'Walery', the 'Brozozowica' landfill site and the arrangement of AWDS transport pipelines (reproduced from Dluzewski et al., [2])

1 - the 'Brzozowica' landfill site
2 - 150mm pipeline
3 - pipeline junction and pump
4 - the 'Lagisza' power station
5 - water drainage pipe
6 - backfill shaft 'Walery'
7 - 150mm pipeline
8 - AWDS storage tank
9 - 150mm pipeline
10 - backfill reservoir
11 - dip heading, seam 501
12 - main heading, level +190
13 - 185 mm vertical pipeline
14 - backfill pipeline

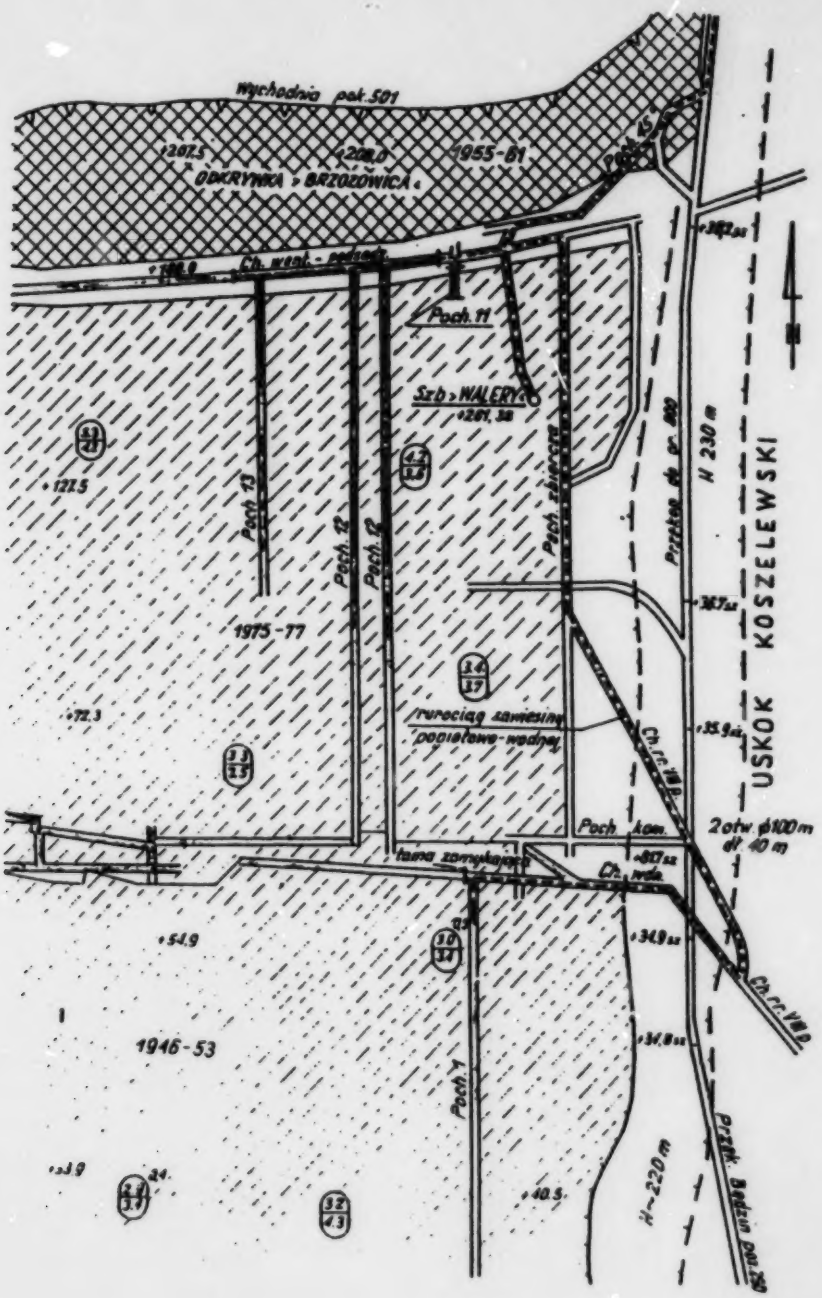


Fig. 3. The use of AWDS for the filling of dip headings in old mine workings, seam 501, 'Gen. Zawadzki' coal mine (reproduced from Ropski and Piotrowski, [39]).

Symbols used in Figs. 3 and 4

- opencast mine site 'Brzozowica' (worked 1955-61)

- old workings with roof collapse, 1946-53 and 1975-77, seam 501

- workings with roof collapse, seam 816

- outcropping, seam 501

- fault line

H 230m - fault displacement

- backfill pipeline

 - stowed area

 - backfill stopping

- direction of water displacement from the workings by AWDS

Ch. - heading

Poch., Up. - dip headings

Przekop - cross heading

Sc. - longwall

Szb. - shaft

bad. - experimental

dost. - supply

kom. - communication

podsadz. - backfill

went., wnt. - ventilation

wodny - water

zbiorcza - collective

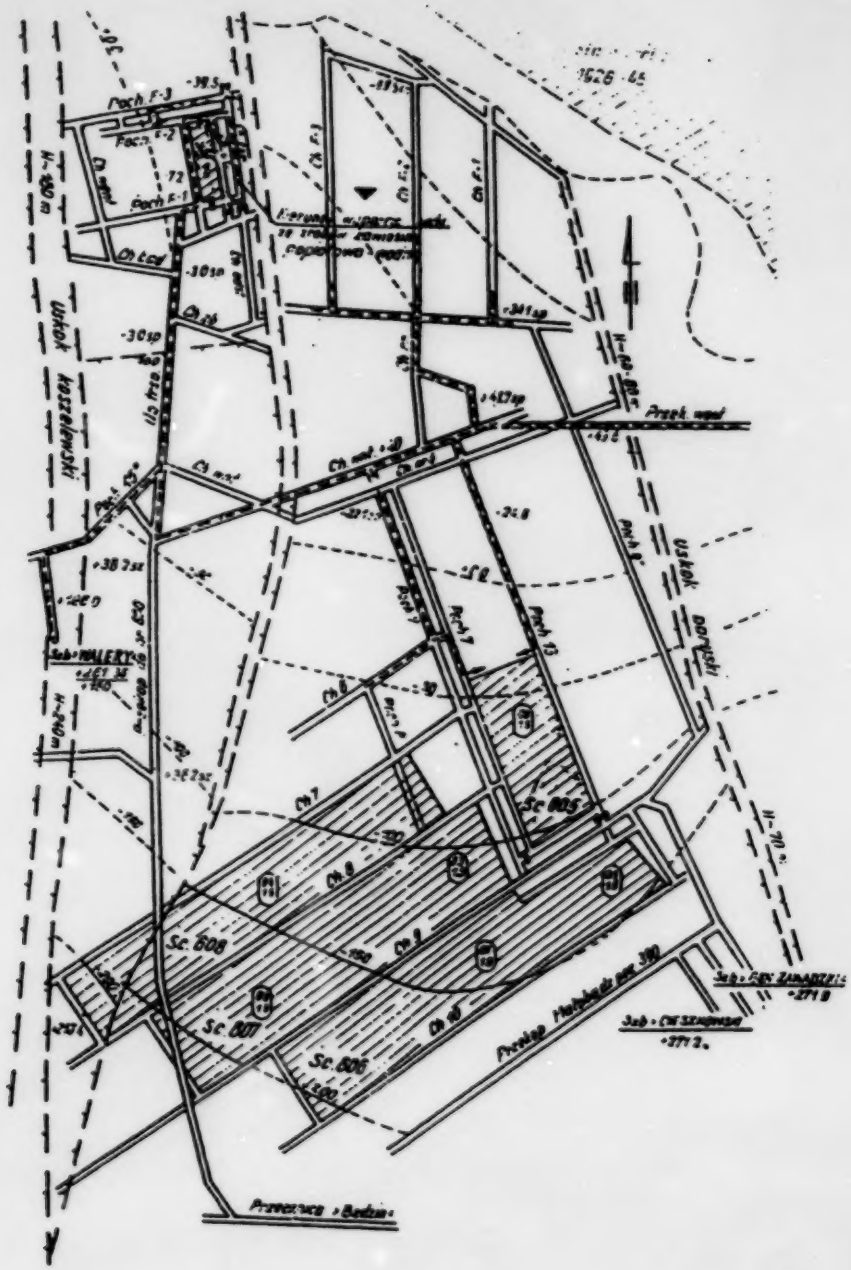


Fig.4. The use of AWDS in seam 816, 'Gen. Zawadzki' coal mine (reproduced from Ropski and Piotrowski [39]).

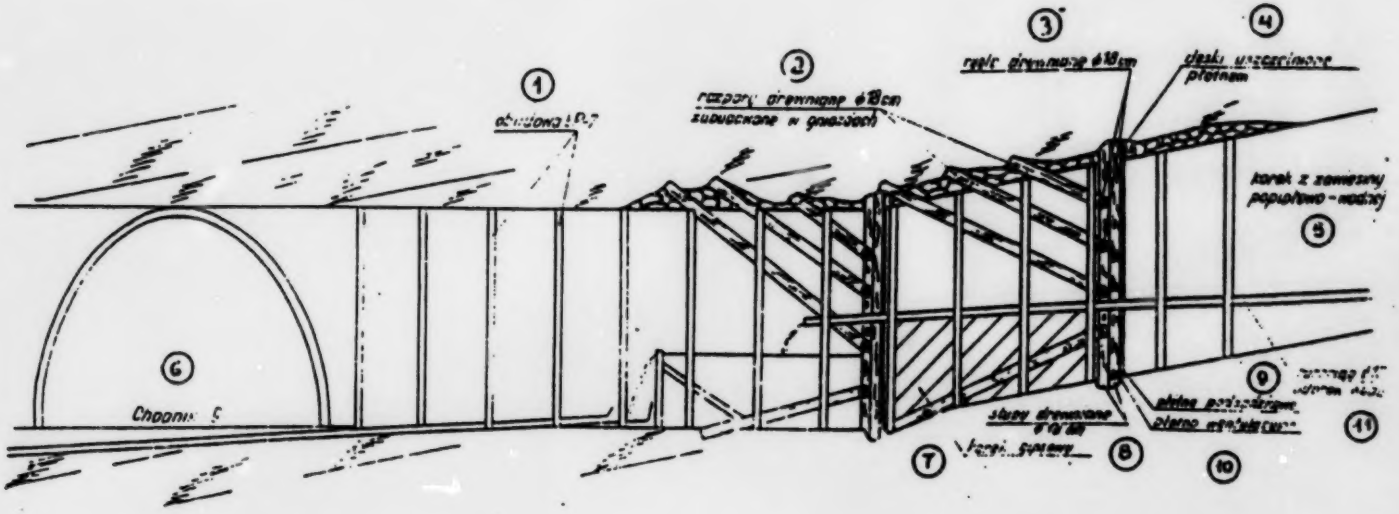


Fig.5. Stopping constructed in dip heading 13, seam 816, 'Gen. Zawadzki' coal mine (after Ropski and Piotrowski [39]).

1 - lining, LP-7
2 - wooden sprags, 18cm diameter, recessed
3 - wooden nogging pieces, 18cm
4 - wooden boards, packed with cloth
5 - AWDS "plug"
6 - heading 9
7 - gypsum "plug"
8 - wooden props, 18cm
9 - backfill cloth
10 - ventilation cloth
11 - water drainage, 100mm pipe

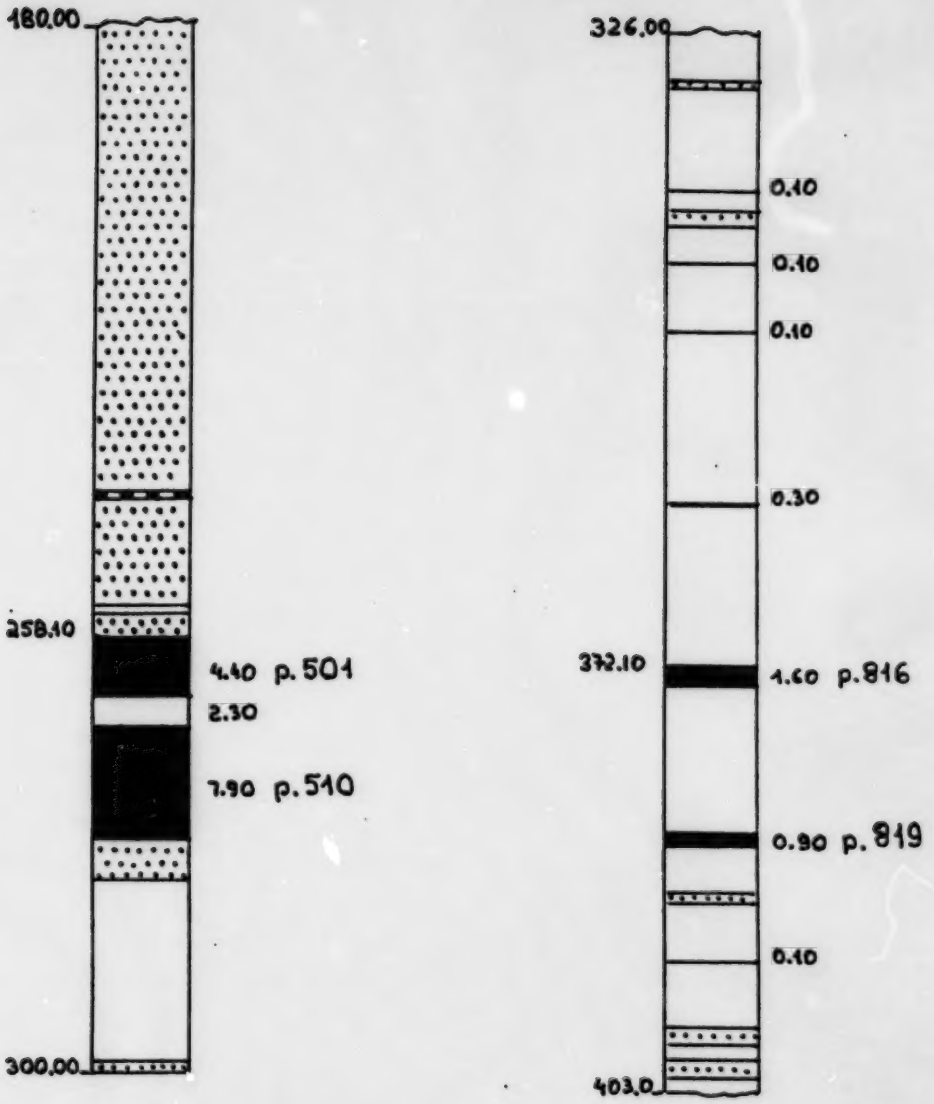


Fig.6. Lithology (simplified) of rock in the roof and floor of coal seams 501-510 and 816, 'Gen. Zawadzki' coal mine
(Based on the lithology of boreholes close to the stowed workings in 501-510 and 816 coal seams. Records kept at the mine).

Scale 1:1000

- claystone, mudstone
- sandstone
- coal
- carbonaceous shale

1800,00 - depth from the surface
4.40 - coal seam thickness

P.501 - coal seam number

Fig.7. **Fly ash utilization in underground mines using the AWDS technology** (Based on Ropski [40] but also including information from other sources [2, 6, 22, 25, 39, 40, 43]).

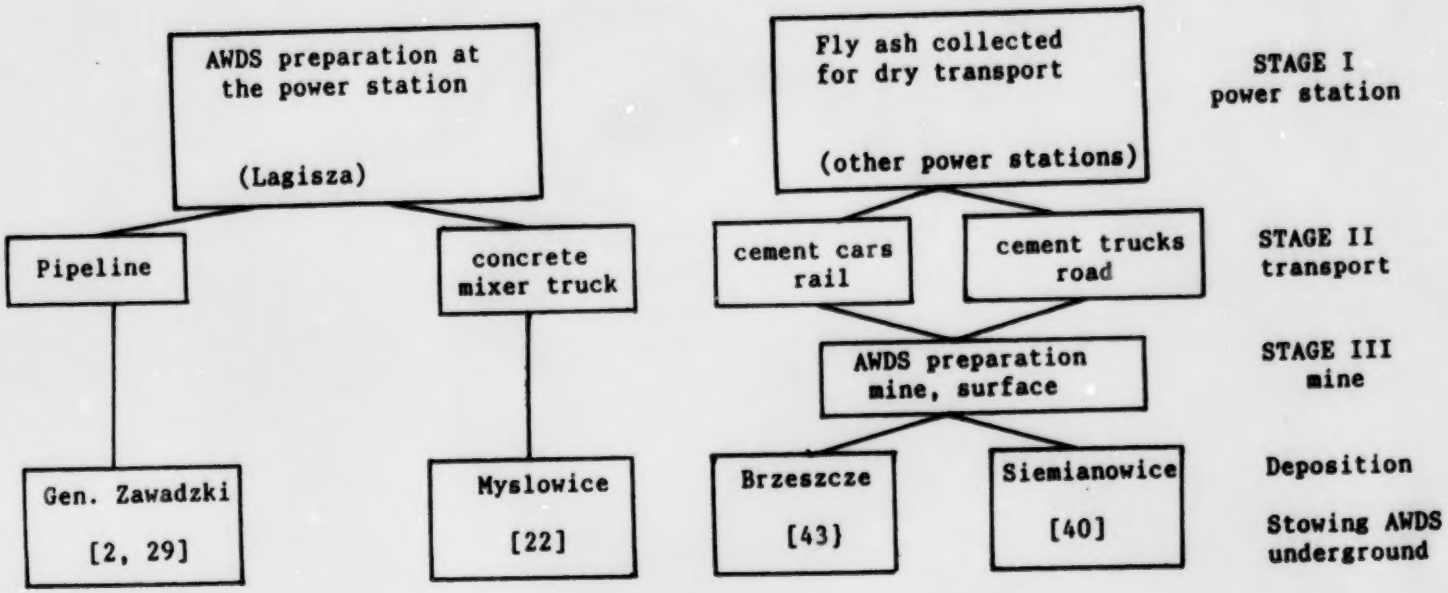
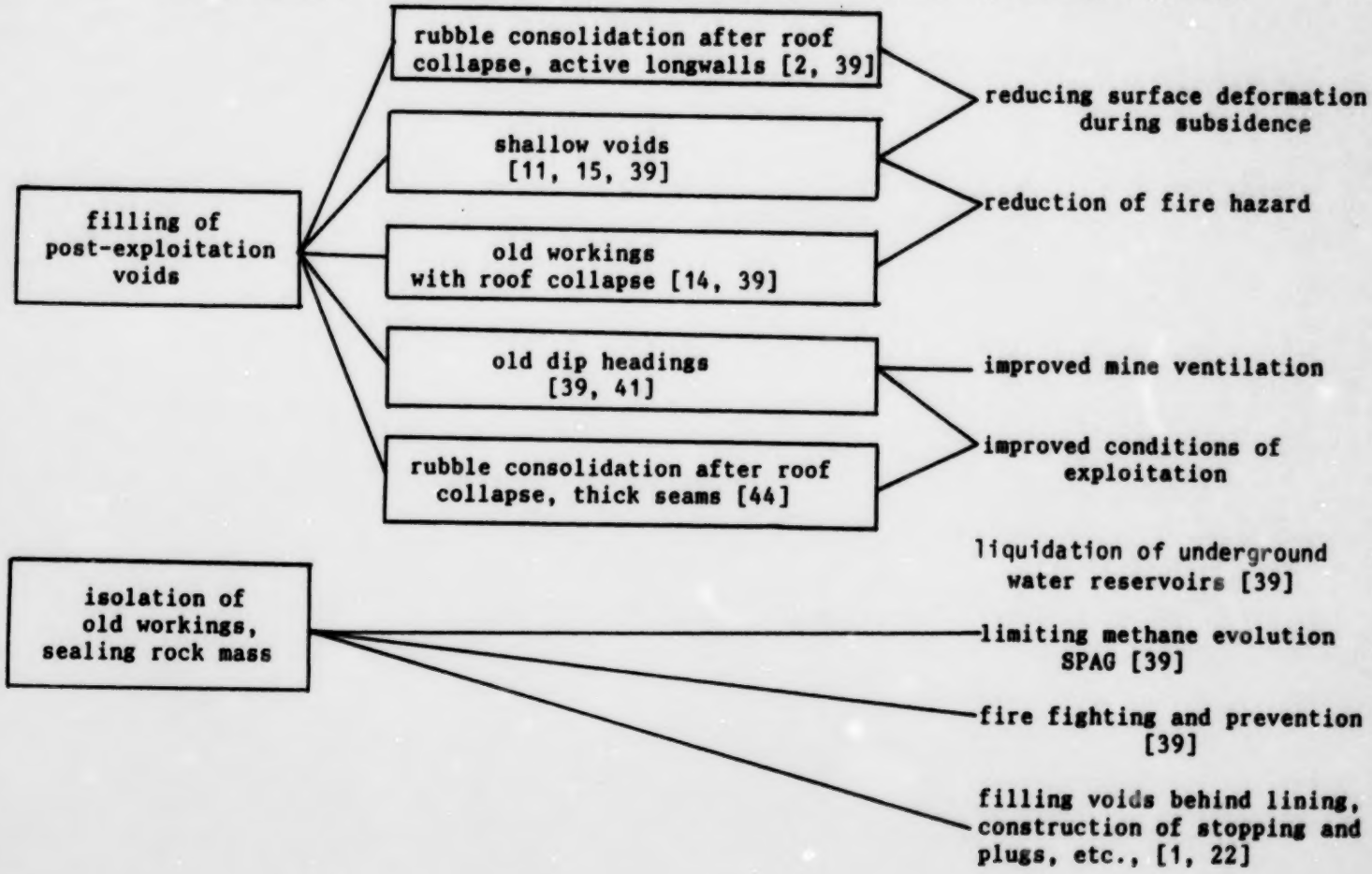


Fig. 8. The utilization of AWDS in underground mines
(Based mainly on [39, 40] and data from [1, 2, 6, 11, 14, 15, 22, 25, 41, 44]).


filling of post-exploitation voids
rubble consolidation after roof collapse, active longwalls [2, 39]
shallow voids [11, 15, 39]
old workings with roof collapse [14, 39]
old dip headings [39, 41]
rubble consolidation after roof collapse, thick seams [44]
reducing surface deformation during subsidence
reduction of fire hazard
improved mine ventilation
improved conditions of exploitation
isolation of old workings, sealing rock mass
liquidation of underground water reservoirs [39]
limiting methane evolution SPAG [39]
fire fighting and prevention [39]
filling voids behind lining, construction of stopping and plugs, etc., [1, 22]

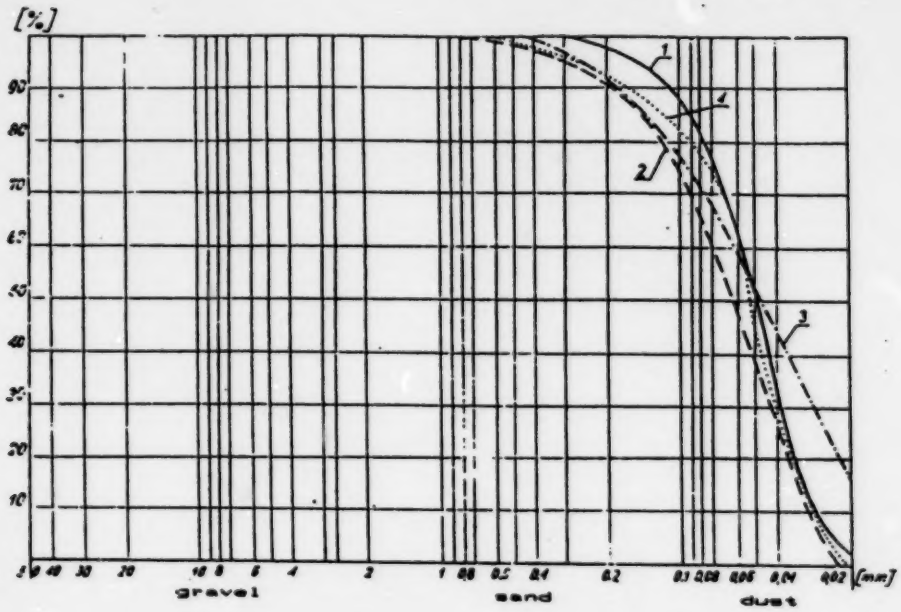


Fig.9. **Particle size distribution for fly ash from different power stations 1 - ' Lagisza', 2 - 'Leg', 3 - 'Jowisz' coal mine, 4 - Zabrze (reproduced from Ropski and Pitrowski [39]).**

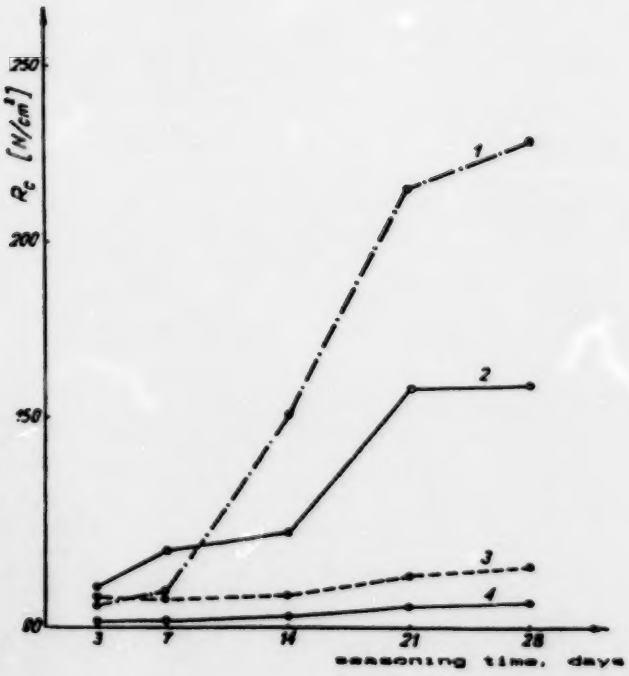


Fig. 10. **Compressive strength of solidified AWDS, change with seasoning time Ash : water ratio 2.0; ash from four power stations: 1-'Zabrze', 2-'Miechowice', 3-'Lagisza', 4-'Jaworzno' (reproduced from Ropski and Pitrowski [39]).**

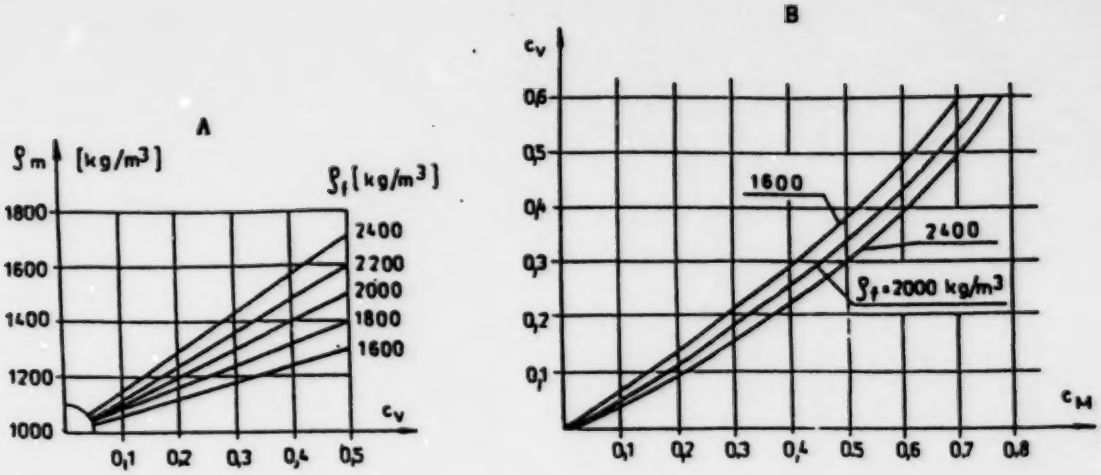


Fig.11. **Fly ash and AWDS - density and concentration relationships (adapted from Rokita and Tomaszewski [34]).**

A. Density of AWDS prepared from ash samples of different densities, as a function of fly ash volume fraction.

B. Fly ash density and the relationship between the volume and mass fractions of soids in AWDS.

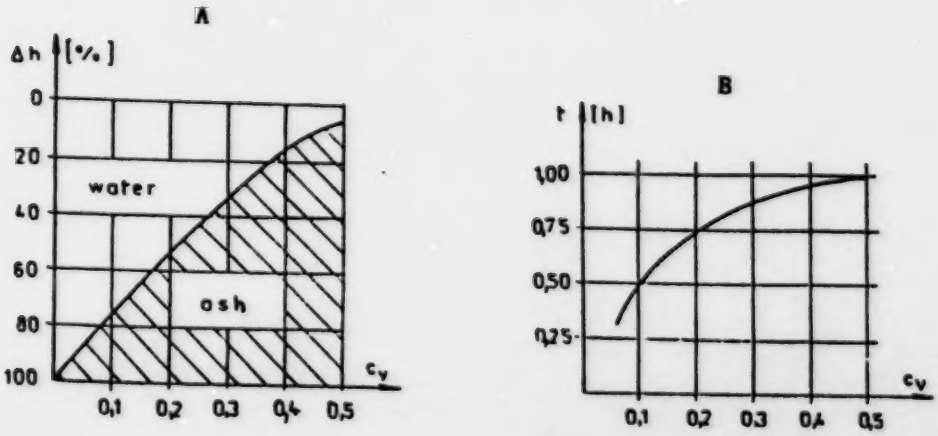


Fig.12. **Sedimentation behaviour of AWDS as a function of fly ash volume fraction (adapted from Rokita and Tomaszewski [34]).**

A. Volume % of supernatant water.

B. Time for fly ash sedimentation in a 150mm pipeline.

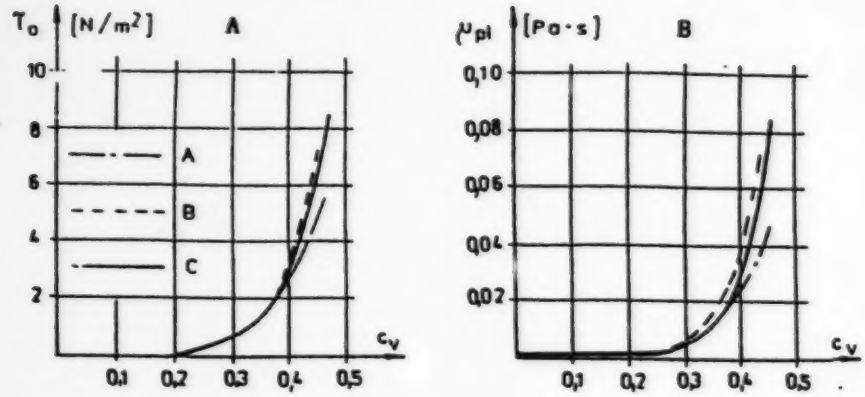


Fig.13. **Rheological properties of AWDS as a function of the fly ash volume fraction (adapted from Rokita and Tomaszewski [34]).**

A. Threshold shearing stress for non-Newtonian behaviour.
B. Plasticity coefficient.

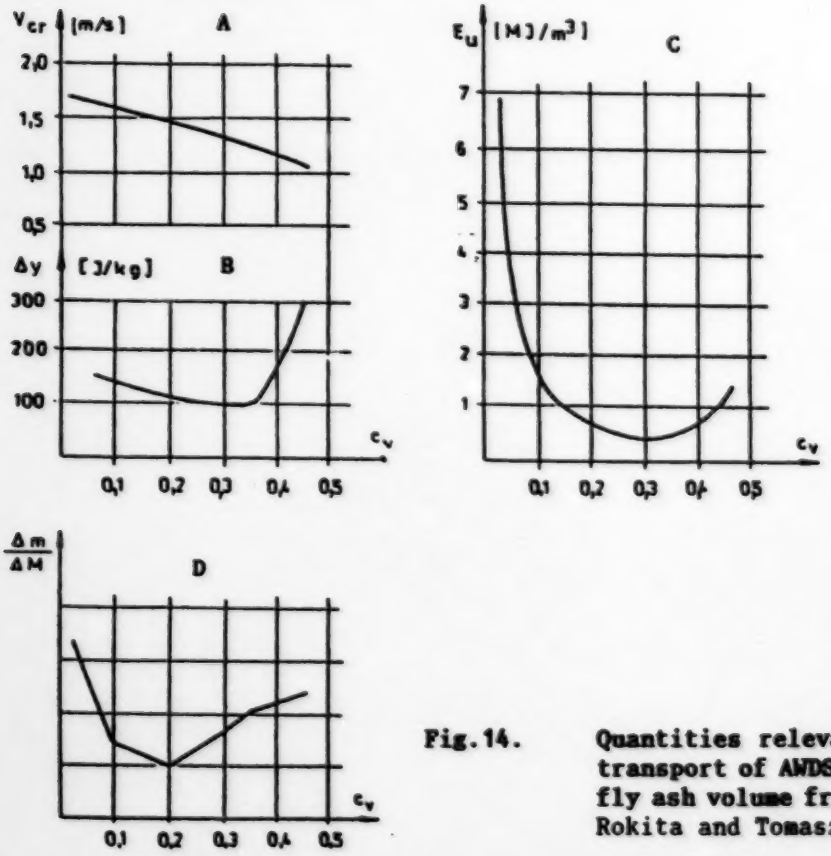


Fig.14. **Quantities relevant to the pipeline transport of AWDS as functions of the fly ash volume fraction (adapted from Rokita and Tomaszewski [34]).**

A. Critical flow velocity. B. Energy loss per unit mass of ash transported. C. Energy required to pump 1m³ of AWDS, at the critical velocity, through a 168mm pipeline 1000m long.
D. Pipeline erosion - ratio of the mass loss of the installation of the mass of fly ash transported as AWDS.

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